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Maximizing Throughput at Soft Airfields

Christopher A. Mouton

RAND
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RAND Project AIR FORCE

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Preface

Aircraft operations on soft fields are limited due to field rutting. Each subsequent aircraft pass, defined as one takeoff and one landing, increases field rutting until the field reaches a point where further aircraft operations are no longer permissible. The ability of aircraft to operate on soft fields is often expressed as a function of aircraft landing weight and the California Bearing Ratio (CBR) of the field, which measures the ability the soil to resist compressive loads. Because soft fields can support only a limited number of takeoffs and landings, it is important to understand how to maximize the cargo throughput at these soft fields. This document shows that there exists an optimum landing weight that allows for maximum cargo delivery. This optimum landing weight is found to be constant and independent of field CBR.

This document reports the soft-field operation findings of a larger fiscal year (FY) 2010 RAND Project AIR FORCE study "Support to the Joint Future Theater Lift Analysis of Alternatives." One of the three objectives of this study was to inform important analytic trade-offs. Understanding the ability of aircraft to operate from soft fields is one of these important trade-offs.

This document details the mathematical calculations used to determine the optimum landing weight that allows for maximum cargo delivery. It should be of interest to analysts studying cargo operations in austere locations.

The research described in this report was sponsored by Major General Susan Desjardins, AMC/A5/8, Robert M. (Mike) Maxwell, AF/A8X, and Richard K. Hartley, SAF/FMC. The study was performed within the Force Modernization and Employment Program of RAND Project AIR FORCE.

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Summary

The number of passes an aircraft can make on a soft field is limited due to the rutting that occurs with each successive landing and takeoff. To quantify the ability of soft fields to support aircraft operations, the California Bearing Ratio (CBR) can be used. In particular, aircraft performance charts often prescribe the number of passes that can be executed based on CBR and aircraft landing weight. As the landing weight increases, the number of allowable passes decreases. However, increased landing weight allows for increased payloads. We examine this trade-off between number of passes and payload in this document.
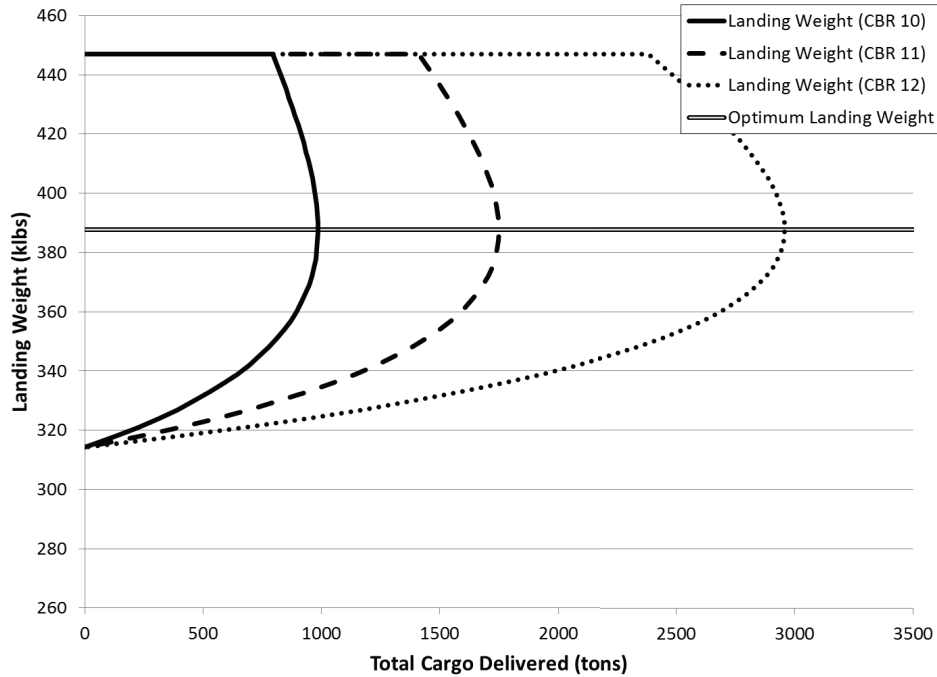
Calculating Optimum Landing Weight

To the extent that a soft field is used for delivery movements, it is important to understand what aircraft landing weights will allow for a given total cargo delivery requirement to be met. This report shows that there exists an optimum landing weight that allows for maximum cargo delivery. This optimum landing weight, defined as the optimum cargo weight per sortie plus the ramp weight at the point of debarkation, is not necessarily the maximum aircraft landing weight. In fact, by landing with a less-than-maximum payload, it is possible that more total cargo could be delivered. The optimum cargo weight, defined as the cargo weight per sortie that yields the maximum total cargo delivery, is found to be constant and independent of both aircraft ramp weight (landing weight minus cargo weight) and field CBR. That is, the optimum cargo weight is independent of the return fuel load as well as the field CBR.

This report also presents the maximum allowable cargo weight given a delivery requirement. This is an important metric because, even though the field damage will be higher than if operations were conducted at the optimum cargo weight, it both minimizes the number of missions that need to be flown and reduces closure time.

Illustrative Calculation: C-17A

We illustrate these calculations using the C-17A, which was one of the options being considered in the joint future theater airlift analysis of alternatives. Figure S.1 shows the optimal landing weight to meet a given delivery requirement, assuming a ramp weight of 315,000 lb. The three curves represent the range of landing weights for various field CBRs, up to and including the maximum allowable landing weight. The figure shows that as the delivery requirement increases, the range of landing weights decreases until the minimum and maximum allowable landing weight converge at the optimum landing weight. Delivery requirements in excess of this optimum cannot be met. The figure also shows that as the CBR is increased, there is a very large increase in the amount of cargo that can be delivered.

Figure S.1. Allowable Range of C-17A Landing Weight Given a Total Cargo Delivery Requirement

In summary, the optimum cargo weight for a C-17A, to maximize the total delivery to a soft field, is about 73,000 lb, subject to aircraft limitations. For example, given a ramp weight of 315,000 lb, a landing weight of about 388,000 lb (73,000 lb of cargo) will allow the maximum cargo delivery to a soft field. If the ramp weight, defined as the aircraft ramp weight for the return leg, were to increase, then the optimum landing weight would increase by an equal amount, the optimum cargo weight would be unchanged, and the total cargo delivered would decrease, all subject to weight limitations of the aircraft.

Conclusions

In general, the optimum landing weight for a C-17A is less than the maximum aircraft landing weight. This optimum landing weight maximizes the amount of cargo that can be delivered to a given field or minimizes the amount of damage to the field for a given fixed delivery requirement. Even if the delivery requirement is less than the maximum capacity of the field, operating at the optimum landing weight may still be effective, since minimizing field damage increases the margin of safety and allows for future operations. Finally, we find that there is a maximum landing weight at which a given cargo requirement can be met. This

maximum landing weight minimizes the number of missions that need to be flown while not exceeding the limits of the soft field.

While the analysis presented here is limited to the C-17A, a similar analysis was done by the author for the C-130J-30. The same functional fit was found for the C-130J-30, although the regression error was slightly higher. This indicates that the results derived in this work will likely apply to other aircraft.

These metrics are important for planning logistical movements to soft fields and can allow for better management and utilization of soft fields. In particular, they will allow planners to define the total cargo delivery capability of various soft fields, which can aid in deliberate and contingency planning.

Acknowledgments

Nomenclature

CBR   California Bearing Ratio

P Number of passes

P^{max} Maximum number of passes a field can support

T_C total cargo delivered (lb)

T_C^{max} total cargo delivered assuming maximum number of passes (lb)

$T_C^{W_L^{max}}$ total cargo delivered assuming maximum number of passes at maximum landing weight (lb)

T_C^* total cargo delivered assuming maximum number of passes and optimal landing weight (lb)

$\overline{T_C^*}$ T_C^* limited by maximum landing weight

W_C payload weight to point of debarkation (lb)

W_C^{lower} minimum cargo weight at which a given cargo throughput can be achieved (lb)

W_C^{upper} maximum cargo weight at which a given cargo throughput can be achieved (lb)

$\overline{W_C^{upper}}$ W_C^{upper} limited by the maximum payload capacity (lb)

W_C^* payload weight at optimal landing weight (lb)

$\overline{W_C^*}$ W_C^* limited by the maximum payload capacity (lb)

W_L landing weight at point of debarkation (lb)

W_L^{max} maximum aircraft landing weight at point of debarkation (lb)

W_R ramp weight at point of debarkation (lb)

1. Introduction

The number of passes an aircraft can make on a soft field is limited because rutting of the field occurs with each successive pass. Eventually, absent resurfacing, this rutting will reach a point where further aircraft operations are no longer permissible. The maximum number of passes an aircraft can make is commonly described as a function of the California Bearing Ratio (CBR) of the field and the weight of the aircraft.

In many situations, CBR is not the best predictor of maximum passes; however, it is frequently used because of the relative ease with which it can be measured and interpreted by pilots. CBR is a measure of the ability of a soil to resist compressive loads; however, landing aircraft put a great deal of shear stress on the field, and this shear stress is responsible for much of the rutting observed in flight operations.[1] The inherent variability and complexity of soil mean that even under the best circumstances accuracy within an order of magnitude is the best that can be expected.[2] Studies show that CBR does not provide a reliable measure in arid and semiarid climates when shear forces are present from braking and turning operations.[3] CBR becomes a more accurate measure of a field's ability to support operations when shear stresses are kept to a minimum, in particular if braking is minimized.[4]

As the landing weight of an aircraft is decreased, the number of passes that the aircraft can make on a given field increases. Given a fixed landing fuel load, any decrease in landing weight entails an equal decrease in payload. The total amount of payload delivered to a field is the product of payload per landing and number of landings. This report will show that there exists an optimum landing weight that will deliver the maximum total payload to a field and that this optimum landing weight is not the maximum landing weight. In particular, landing at a lower weight can increase the number of allowable passes faster than the payload decreases, resulting in a larger total delivery.

---

[1] Jeb S. Tingle, "Testing and Analysis of C-17 Live-Flight Operations on Semi-Prepared Airfields," Technical Report GL-98-11, USAE Waterways Experiment Station, Vicksburg, Miss., June 1998.

[2] William P. Grogan and Jeb S. Tingle, "Evaluation of Unsurfaced Airfield Criteria," *Journal of Transportation Engineering*, Vol. 125, No. 1, January/February 1999.

[3] Jeb S. Tingle and William P. Grogan, "Behavior of Unsurfaced Airfields Supporting Operations of C-17 Aircraft," *Journal of Transportation Engineering*, Vol. 125, No. 1, January/February 1999.

[4] Tingle and Grogan, "Evaluation of Unsurfaced Airfield Criteria."

Purpose and Organization of This Report

This document is part of a larger PAF study that provided support to the joint future theater lift analysis of alternatives. The purpose is to highlight the analytic trade-offs involved in operating aircraft from soft fields. Chapter Two details the calculations we used to determine the optimum landing weight to deliver the maximum total payload to a soft field. Chapter Three illustrates how these calculations are applied using the C-17A. Chapter Four summarizes our overall conclusions.

2. Calculating Optimum Landing Weight

Performance charts for aircraft designed to operate on soft fields, such as the C-17A and C-130J, often present a table relating the maximum number of passes that aircraft can achieve as a function of the weight of the aircraft and the CBR of the field. These charts assume that there is no runway resurfacing during operations, which could drastically increase the total number of passes. It was found that these performance data could be fit with an equation of the form

$$P^{max} = a\text{CBR}^b e^{-cW_L}, \tag{1}$$

where P^{max} is the maximum number of passes and W_L is the landing weight. The coefficients a, b, and c are fit to the data using regression analysis.

The landing weight can be broken up into two components. The first is the payload, or cargo weight, W_C. The second is the ramp weight, W_R, which is defined as the landing weight minus the cargo weight,

$$W_R = W_L - W_C. \tag{2}$$

Therefore, the maximum number of passes an aircraft can make in terms of cargo weight is

$$P^{max} = a\text{CBR}^b e^{-c(W_R + W_C)}. \tag{3}$$

Assuming the maximum number of passes and given a ramp weight and cargo weight, the total cargo delivered, T_C^{max}, is simply the number of landings times the cargo of each landing. Since a pass represents one takeoff and one landing, the number of passes equals the number of landings and the total payload delivered can be written as

$$T_C^{max} = aW_C\text{CBR}^b e^{-c(W_R + W_C)}. \tag{4}$$

To maximize the total payload delivered, this equation can be differentiated with respect to W_C. In this case, W_R is assumed to be independent of the cargo weight, since W_R would consist of the operating empty weight of the aircraft, fuel reserves, and any recovery fuel. We find the derivative of Equation 4 with respect to the cargo weight to be

$$\frac{dT_C^{max}}{dW_C} = a\text{CBR}^b e^{-c(W_R + W_C)}(1 - cW_C). \tag{5}$$

3

An extrema, a maximum or a minimum, of T_C^{max} occurs when this derivative is equal to zero. The derivative is equal to zero at a critical value of W_C, which is denoted W_C^*:

$$aCBR^b e^{-c(W_R + W_C^*)}(1 - cW_C^*) = 0. \tag{6}$$

This equation is only satisfied if

$$W_C^* = \frac{1}{c}. \tag{7}$$

We can verify that this critical value represents a maximum by looking at the second derivative of T_C at this point. Doing so shows us that

$$\left. \frac{d^2 T_C^{max}}{dW_C^2} \right|_{W_C = W_C^*} = -acCBR^b e^{-c(W_R + W_C^*)}. \tag{8}$$

Since weights and CBR are always positive, the extrema is a maximum if a and c have the same sign. Since the number of passes is always positive, a must be positive, and since the number of passes always decreases with increasing landing weight, c must also be positive. This therefore shows that the critical cargo weight W_C^* maximizes the total cargo delivered.

It is interesting to note that the optimum cargo weight is independent of both the ramp weight and CBR, i.e., the optimum cargo weight is independent of the landing fuel load and of the field on which operations are being conducted. The maximum total cargo that can be delivered to a field at the optimum landing weight, T_C^*, is

$$T_C^* = \frac{aCBR^b}{ce^{1 + cW_R}}. \tag{9}$$

It is possible that the combination of optimum cargo weight and ramp weight may exceed the maximum landing capability of the aircraft, W_L^{max}. Other factors, such as range limitations, maximum gross takeoff weight (MGTOW) at the point of embarkation, critical field length, and landing distance over a 50-foot obstacle, may further limit landing and takeoff weight. These factors can easily be incorporated into the definition of W_L^{max}; however, for simplicity these limits are not directly considered in this analysis. Since the total delivery is a concave function of cargo weight, we can define a bounded optimum landing weight, $\overline{W_C^*}$, as

$$\overline{W_C^*} = min(W_L^{max} - W_R, W_C^*). \tag{10}$$

And similarly, the bounded maximum payload delivery, $\overline{T_C^*}$, is

$$\overline{T_C^*} = a\overline{W_C^*}CBR^b e^{-c(W_R+\overline{W_C^*})}. \tag{11}$$

In all cases, $\overline{T_C^*}$ is greater than or equal to the delivery at maximum landing weight, where the total delivery at maximum landing weight, $T_C^{W_L^{max}}$, is given by

$$T_C^{W_L^{max}} = a(W_L^{max} - W_R)CBR^b e^{-cW_L^{max}}. \tag{12}$$

For delivery requirements more than $\overline{T_C^*}$, there is no way to meet the total delivery requirement. For a delivery requirement equal to $\overline{T_C^*}$, landings must occur with a cargo load of $\overline{W_C^*}$. For delivery requirements less than $\overline{T_C^*}$, there is a range of cargo loads that can meet the requirement. This range can be expressed as a minimum and maximum allowable cargo load. This can be found by solving Equation 4 for W_C, which will have two solutions since T_C is a concave function of W_C. The two solutions for W_C, W_C^{lower} and W_C^{upper}, are

$$W_C^{lower} = -\frac{w_0\left(-\frac{cT_C e^{cW_R}}{aCBR^b}\right)}{c}, \tag{13}$$

$$W_C^{upper} = -\frac{w_{-1}\left(-\frac{cT_C e^{cW_R}}{aCBR^b}\right)}{c}, \tag{14}$$

where w is the product log function, also known as the Lambert W-function, and the subscript denotes the branch cut with w_0 being the principal value. The lesser of W_C^{upper} and the maximum cargo weight is denoted $\overline{W_C^{upper}}$.
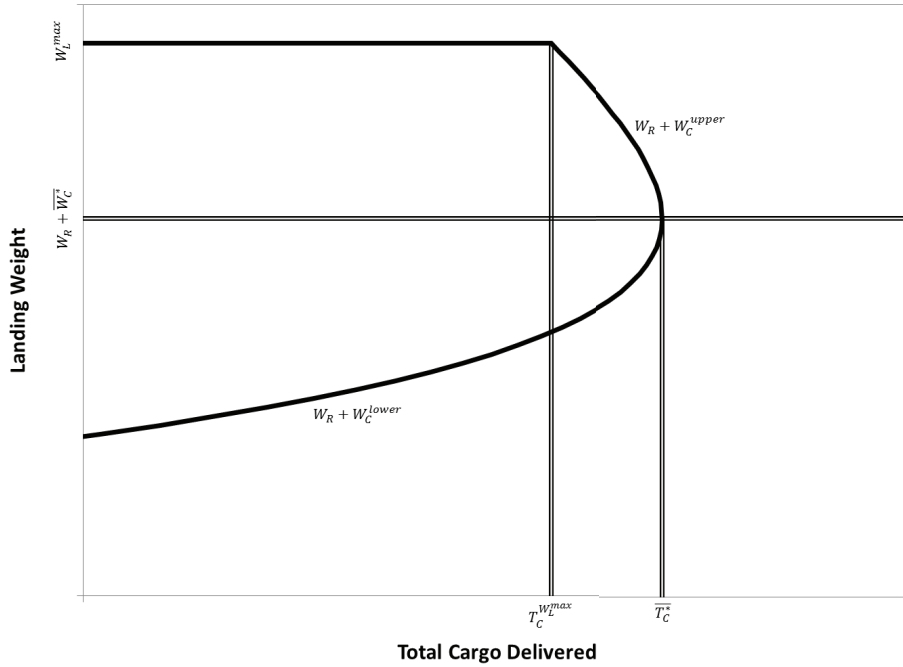
To summarize, the range of landing weights that will allow the delivery requirement to be met is given in Table 2.1. Note that landing at a weight higher or lower than the optimum landing weight will result in additional field damage for the same total cargo, which reduces margins of safety and also reduces the availability of the field for future contingencies. Operating at the maximum landing weight has the benefit of reducing the number of missions. Specifically, landing with a cargo load of $\overline{W_C^{upper}}$ will minimize the total number of missions while still being able to meet the delivery requirement.

Table 2.1. Landing Weights for Various Delivery Requirements

	$T_C <= T_C^{W_{L_{max}}}$	$T_C^{W_{L_{max}}} < T_C < \overline{T_C^*}$	$T_C = \overline{T_C^*}$	$T_C > \overline{T_C^*}$
Minimum landing weight	$W_R + W_C^{lower}$	$W_R + W_C^{lower}$	$W_R + \overline{W_C^*}$	N/A
Optimum landing weight	$W_R + \overline{W_C^*}$	$W_R + \overline{W_C^*}$	$W_R + \overline{W_C^*}$	N/A
Maximum landing weight	W_L^{max}	$W_R + W_C^{upper}$	$W_R + \overline{W_C^*}$	N/A

Figure 2.1 presents a graphical representation of the critical values presented in Table 2.1. In particular, the figure shows that the maximum cargo delivery for which there is an associated landing weight is $\overline{T_C^*}$. The landing weight associated with this maximum total cargo delivery is $W_R + \overline{W_C^*}$. The maximum total cargo that can be delivered when landing at the maximum allowable landing weight, W_L^{max}, is also shown on the figure as $T_C^{W_L^{max}}$. In addition, the figure shows the two possible solutions for the landing weight, $W_R + W_C^{upper}$ and $W_R + W_C^{lower}$, when the cargo delivery requirement is less than the maximum possible total cargo delivery. Note that the upper bound is only defined when the cargo delivery requirement is greater than $T_C^{W_L^{max}}$.

Figure 2.1. Critical Values of Landing Weight and Total Cargo Delivered

3. Boeing C-17A Analysis

CBR data were sampled from the figure entitled "Runway Weight Bearing Capacity on Unpaved Runways Using CBR Rating with Standard Tire Pressures" from the C-17 Technical Description and Planning Guide, based on a 32-percent mean aerodynamic chord center-of-gravity limit, at landing weights of 280,000 lb, 300,000 lb, 350,000 lb, 400,000 lb, and 447,000 lb, and for 50, 100, and 300 passes.[5] In particular, a pass is defined as one takeoff and one landing. Using the form for the maximum number of passes, as given in Equation 1,

$$P^{max} = a\text{CBR}^b e^{-cW_L}, \tag{15}$$

we can solve for the three coefficients using the 15 data samples from the C-17 Technical Description and Planning Guide's soft field performance chart that are shown as open circles in Figure 3.1. The following coefficients were found to fit these data:

$$a = 4.9262 \text{ x } 10^{-3}, \tag{16}$$
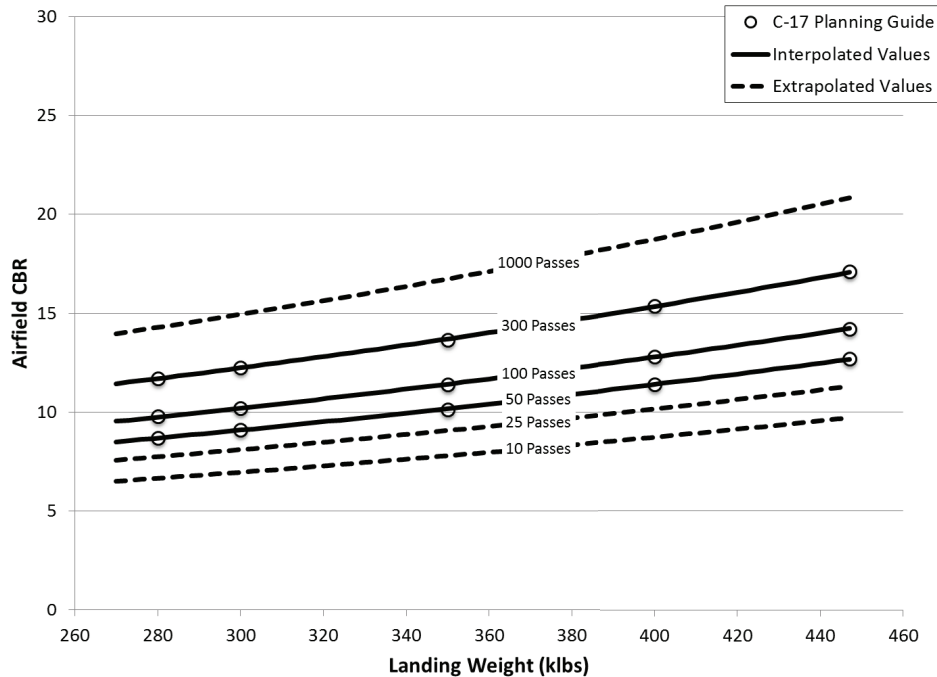$$b = 6.0384, \tag{17}$$
$$c = 1.36842 \text{ x } 10^{-5} \text{ (1/lb)}. \tag{18}$$

This produces an R^2 value of 0.9995 and, as Figure 3.1 shows, it produces a very good data fit. The solid lines represent a constant number of passes, based on Equation 1, and the numbers overlaid on the lines represent the corresponding number of passes.

Note that in Figure 3.1, the curves for more than 300 passes or less than 50 passes are shown as dashed lines since these values are extrapolated. There are no data to support this extrapolation, and further testing would have to be done to verify its validity. However, for the purposes of deriving an optimum weight, this extrapolated region will be included in the final results.

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[5] "C-17 Globemaster III: Technical Description and Planning Guide," Long Beach, Calif.: Boeing, 2002.
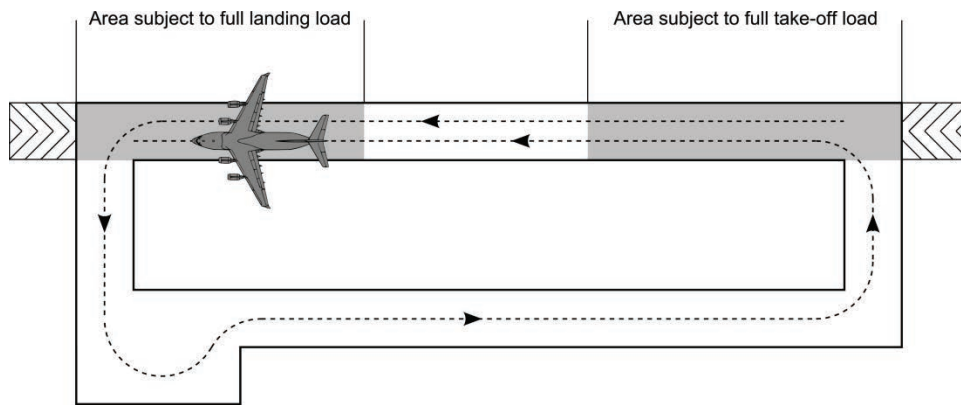
Figure 3.1. Curve Fit of C-17A Number of Passes Data

These results, which are derived based on the C-17 Technical Description and Planning Guide, define a *pass* as one takeoff and one landing. The Planning Guide presents the number of passes as a function of gross weight; however, since the landing weight is the limiting factor, the landing weight is used in this analysis. In addition, the Planning Guide does not assume additional runway passes due to ground operations such as back-taxiing. To illustrate this, consider Figure 3.2, which corresponds to the analysis presented here.[6] The figure shows two separate runway areas subjected to the full load of the aircraft, that is, two areas where the aircraft operates with little to no lift. In particular, the upwind portion of the airfield is subjected to the full landing load and the downwind portion of the airfield is subjected to the full takeoff load. Given that these are separate regions, the area subjected to the full landing load will experience the greatest degradation and will define the limit of the airfield to support operations.

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[6] Richard B. Smith, HQ AFCESA/CESC, "Contingency Airfield Pavement Evaluation," Washington, D.C.: Headquarters U.S. Air Force, 2004.

Figure 3.2. Layout of Airfield Ground Operations

With the coefficients given in Equations 16 to 18, the maximum number of passes from Equation 1 and the total tons delivered can be plotted as a function of landing weight, assuming a ramp weight, W_R , of 315,000 lb. A ramp weight of 315,000 lb is approximately sufficient to allow for a 500nm recovery and for sufficient reserve fuel. Figure 3.3 shows the nonlinear decrease in maximum number of passes as landing weight increases, along with the linear increase of payload weight with increasing landing weight. This product of payload weight and number of passes produces a concave relationship between total tons delivered and landing weight (see Figure 3.4). As noted earlier, the optimum landing weight for maximum payload delivery is independent of CBR. Figure 3.4 shows that for total delivery requirements less than the maximum delivery, there is a range of landing weights that can meet the requirement.

Figure 3.3. Number of Passes and Payload Capacity as a Function of Landing Weight and CBR for the C-17A
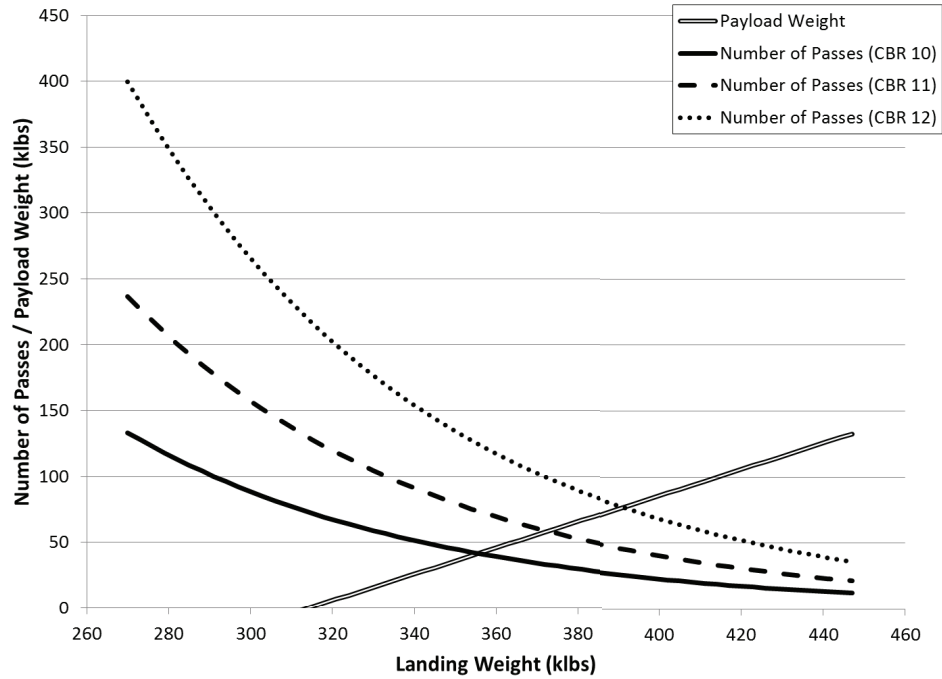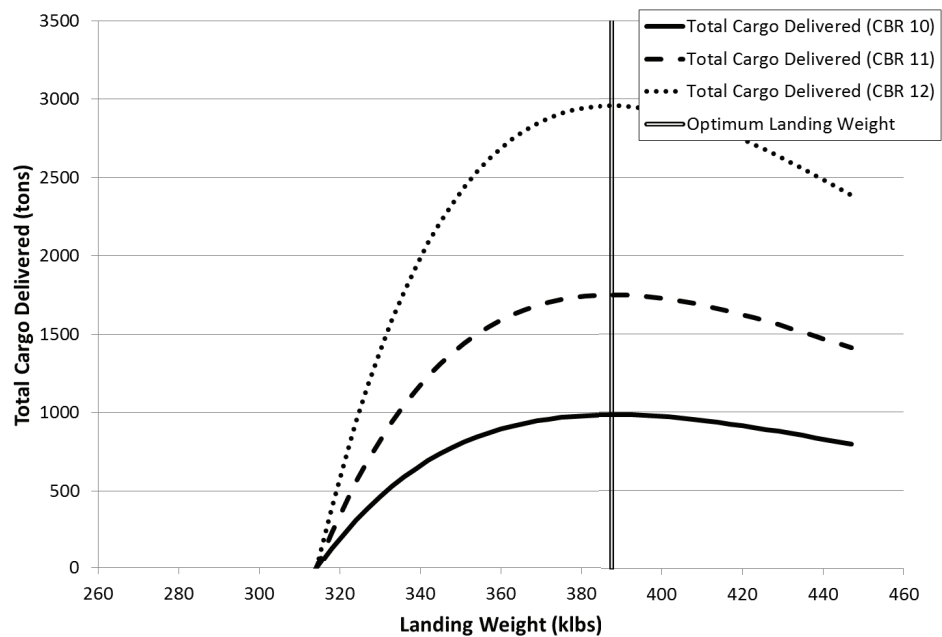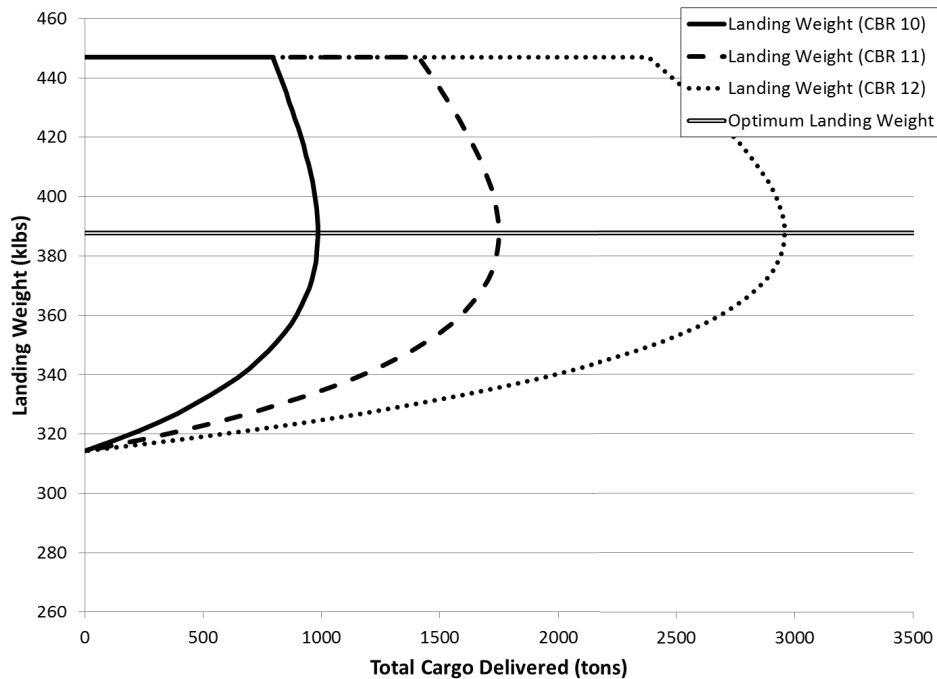

Figure 3.4. Total Cargo Delivery as a Function of Landing Weight and CBR for the C-17A

Given the same ramp weight of approximately 315,000 lb, the range of landing weights that can meet the delivery requirement, along with the optimum landing weight, is plotted in Figure 3.5. The horizontal line at approximately 388,000 lb represents the optimal landing weight. The curve above this optimal landing weight corresponds to the lesser of the maximum cargo weight and W_C^{upper}, and the curve below this optimal landing weight corresponds to W_C^{lower}. Therefore, the allowable landing weight range is the range of weights between the lower curve and upper curve for a given CBR value. The figure shows that as the delivery requirement increases, the range of landing weights decreases until the minimum and maximum allowable landing weight converge at the optimum landing weight, beyond which the delivery requirement can no longer be met. The figure also shows that as the CBR is increased there is a very large increase in the amount of cargo that can be delivered.

Figure 3.5. Allowable Range of C-17A Landing Weight Given a Total Cargo Delivery Requirement

As mentioned previously, any cargo weight between W_C^{lower} and the lesser of the maximum cargo weight and W_C^{upper} can meet the delivery requirement; however, operating at higher cargo weights will require fewer missions.

The number of missions required to deliver a given cargo requirement, as a function of CBR, is plotted in Figure 3.6. In this case, the linearly increasing line corresponds to the optimal payload, which is less than the maximum allowable payload. The portion of the curve above the

optimal payload corresponds to cargo weights equal to W_C^{lower}, and the portion of the curve below the optimal payload corresponds to cargo weights equal to the lesser of the maximum cargo weight and W_C^{upper}. The lower curve displays a linear section since the payload is limited by the maximum payload capacity. Even though the field would be able to support higher-weight landings, the aircraft limits do not allow it. The figure also shows that there can be significant savings in terms of the number of missions, which equals number of passes, by operating at weights higher than the optimal landing weight; however, this would leave a lesser margin of safety in terms of airfield quality and would reduce the ability of the field to support future missions.

Figure 3.6. Number of C-17A Missions Required to Deliver a Given Amount of Cargo
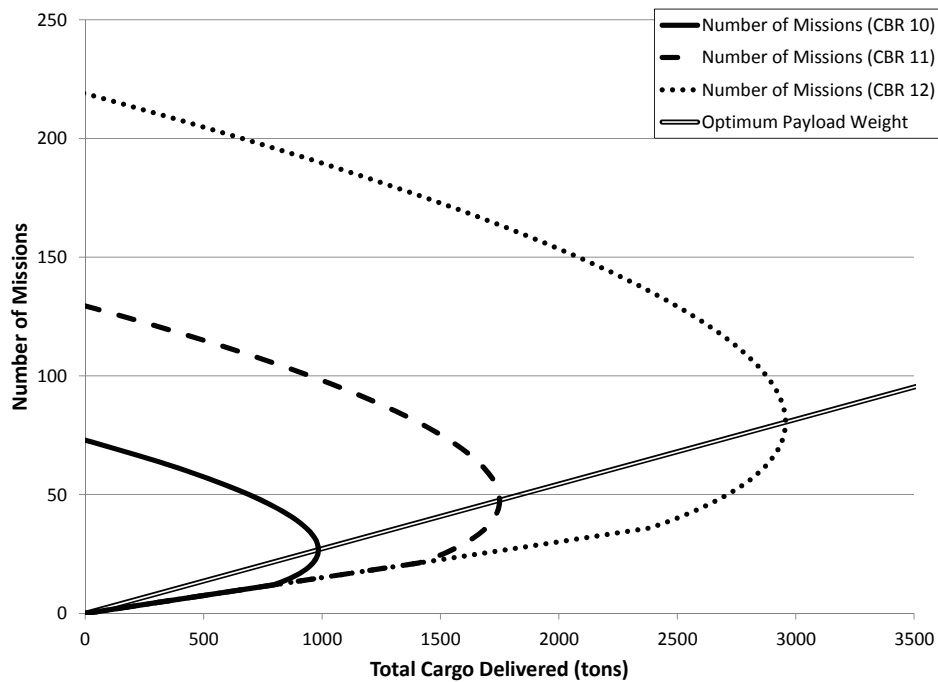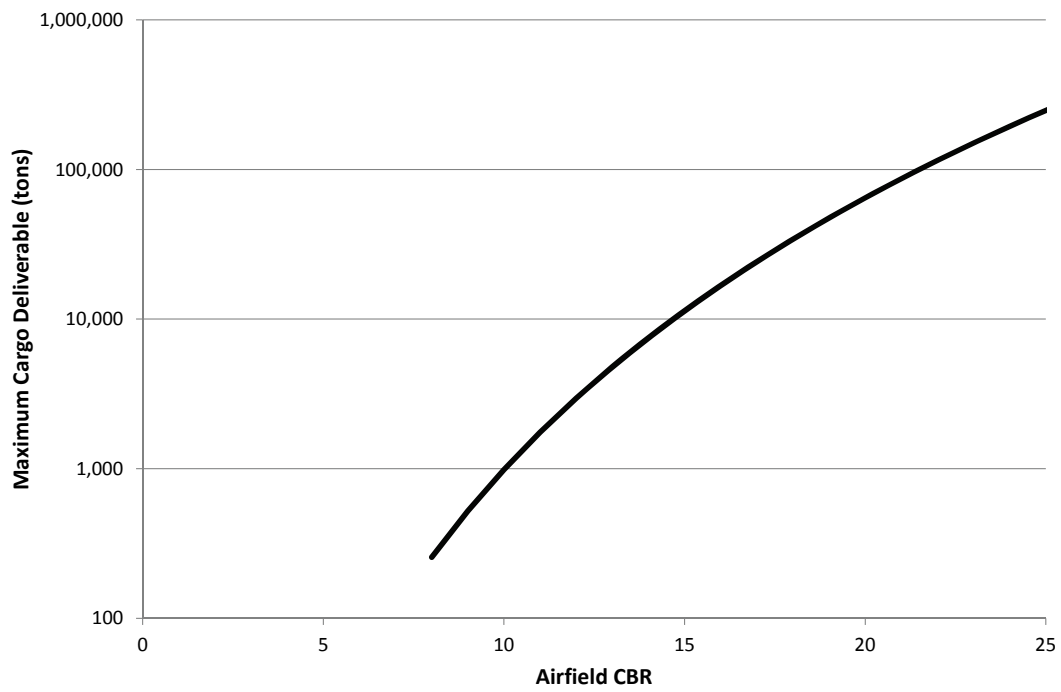

Figure 3.7 shows a significant increase in the amount of cargo that can be delivered as CBR increases, again assuming a 315,000-lb ramp weight at the landing zone. This is consistent with the findings of Equation 9, which shows that the total cargo delivered increases exponentially with CBR.

Figure 3.7. Maximum Cargo Deliverable by C-17A to a Field of a Given CBR

4. Conclusions

Based on the preceding analysis, we derive several important observations and calculations regarding aircraft operations on soft fields.

First, we show that for a given fixed ramp weight, there exists an optimum landing weight and that this optimum landing weight is not equal to the maximum aircraft landing weight. This optimum landing weight can also be expressed as an optimum cargo weight, and this optimum cargo weight is found to be independent of both field CBR and aircraft ramp weight. In fact, for the C-17A with a ramp weight of 315,000 lb, the optimum landing weight is less than the maximum aircraft landing weight. This optimum landing weight maximizes the amount of cargo that can be delivered to a given field; given a fixed delivery requirement, it minimizes the amount of damage to the field. Even if the delivery requirement is less than the maximum capacity of the field, operating at the optimum landing weight may still be effective since minimizing field damage increases the margin of safety and allows for future operations.

As an example, in the case of the C-17A, the optimum cargo weight for a sortie is about 73,000 lb of cargo, which is independent of ramp weight and CBR. For instance, with a ramp weight of 315,000 lb, the optimum landing weight is about 388,000 lb. Other factors, such as range limitations, MGTOW at the point of embarkation, critical field length, and landing distance over a 50-foot obstacle, may limit the amount of cargo that can be carried to below 73,000 lb. In this case, the cargo throughput can be maximized, although at a lower level, by carrying the maximum allowable cargo load.

Second, we show that there exists a maximum landing weight at which a given cargo requirement can be met. This maximum landing weight minimizes the number of missions that need to be flown while not exceeding the limits of the soft field.

Both of these metrics are important for planning logistical movements to soft fields and can allow for better management and utilization of soft fields.

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